Analysis of PMTs, SBPMTs, and VSTs in a Stiff Clay of Quebec

Analyse des essais PMT, SBPMT et VST dans une argile raide du Québec

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ABSTRACT

The objective of the present paper is to compare field test results obtained in a stiff sensitive clay of Quebec using pre-bored pressuremeter tests (PMTs) with those obtained from both self-boring pressuremeter tests (SBPMTs) and vane shear tests (VSTs). It is shown that the undrained shear strength S_u deduced from PMTs is greatly overestimated with respect to the values found from SBPMTs and VSTs. Discrepancies are thought to arise from both initial disturbance and unloading caused by drilling of the pilot holes prior to the performance of the PMTs. The paper demonstrates that it is possible to combine the expansion curves found in the PMTs with those determined in the SBPMTs to obtain a better insight of the deformation mechanisms involved in the expansion process.

RESUME

L'objectif du présent article est de comparer les résultats d'essais sur place obtenus dans une argile raide sensible du Québec en utilisant des essais pressiométriques préforés (PMT) avec ceux obtenus à partir d'essais pressiométriques autoforeurs (SBPMT) et d'essais au scissomètre (VST). Il est démontré que la résistance au cisaillement non drainé S_u déduite des PMT est grandement surestimée par rapport aux valeurs trouvées à partir des SBPMT et des VST. On croit que les écarts résultent à la fois du remaniement initial et du déchargement causés par le forage des trous pilotes avant que les PMTs soient effectués. L'article démontre qu'il est possible de combiner les courbes d'expansion déduites des PMTs avec celles déterminées à partir des SBPMTs pour obtenir un meilleur aperçu des mécanismes de déformation impliqués dans le processus d'expansion.

Keywords: Pre-bored and self-boring pressuremeter tests, stiff sensitive clay, loading-unloading curves, Masing model.

1. Introduction

Pressuremeter testing can be divided in two main categories: prebored and self-bored pressuremeter tests (Ferreira and Robertson 1992). The prebored pressuremeter test (PMT) is performed in a predrilled pilot hole, whereas the self-boring pressuremeter test (SBPMT) is self-bored in place to minimize unloading of the borehole and installation disturbance. Theoretical analyses of SBPMTs in clay have developed so that it is possible in principle to determine the complete stress-strain response and not only the shear modulus G, the undrained shear strength S_u, and the in situ horizontal geostatic stress σ_{ho} (Pye 1995).

However, as experience has accumulated over the years with the SBPMT, it has been found that some installation disturbance still occurs affecting the initial part or more of the resulting pressuremeter curve (Eden and Law 1980; Benoit and Clough 1986; Prapaharan et al. 1990; Jefferies and Shuttle 1995; Aubeny et al. 2000). In an attempt to obtain true undisturbed shear strength parameters, various investigators suggested several years ago to put more emphasis on the last segment of the loading branch and on the contraction phase of the pressuremeter curve (Jefferies 1988; Houlsby and Withers 1988; Ferreira and Robertson 1992). While Jefferies (1988) and Houlsby and Withers (1998) extended the work of Gibson and Anderson (1961) based upon the classical linearly elastic-perfectly plastic Tresca model, Ferreira and Robertson (1992) proposed a hyperbolic model following the work of Denby and Cough (1980). It should be noted that these investigators assumed that both S_u and G remained constant in the loading-unloading branches of the elastic-plastic and hyperbolic models.

The objective of the present paper is to determine whether the performance of contraction phases in strain-controlled PMTs could improve the quality of data and aid in the analysis of the pressuremeter curves, as suggested by the previous investigators in the case of SBPMTs. A field investigation was carried out by means of expansion-contraction PMTs in a stiff sensitive clay of Quebec. For comparison purposes, loading SBPMTs were also carried out in the same clay deposit, together with field vane shear tests (VSTs). The results show that the pressuremeter curves deduced from the strain-controlled PMTs may be considered as reload-unload cycles centered around the pressuremeter curves obtained from SBMTs, which constitute, in a certain way, backbone or skeleton curves, as shown by Prevost (1979).

2. Theoretical Analyses

PMT and SBPMT curves are first interpreted by assuming that clay response can be represented either by a classical Tresca model or by a hyperbolic model. Second, Palmer's approach is used for the analysis of SBPMT loading data.

2.1. Elastic-Plastic Model

a) Loading

The constitutive relationships in loading are the following material (Cassan 1960; Gibson and Anderson 1961):

$$\tau = G\gamma, \gamma \leq S_u/G \quad (1a)$$

$$\tau = S_u, \gamma > S_u/G \quad (1b)$$

where τ is the shear stress and γ is the shear strain. The corresponding radial expansion pressure-shear strain relationships are the following:

$$p = p_o + G\gamma, \gamma \leq S_u/G \quad (2a)$$

$$p = p_o + S_u(1 + \ln I_r\, \gamma), \gamma > S_u/G \quad (2b)$$

where p is the applied radial pressure, p_o is the initial horizontal pressure existing in the soil prior to the performance of the pressuremeter test, and $I_r = G/S_u$ is the rigidity index.

b) Unloading

For the unloading phase of the test, Eqs. 1 and 2 become respectively:

$$\tau^* = G^*(\gamma_{max} - \gamma), (\gamma_{max} - \gamma) \leq S_u^*/G^* \quad (3a)$$

$$\tau^* = S_u^*, (\gamma_{max} - \gamma) > S_u^*/G^* \quad (3b)$$

and

$$p = p_{max} - G^*(\gamma_{max} - \gamma), (\gamma_{max} - \gamma) \leq S_u^*/G^* \quad (4a)$$

$$p = p_{max} - S_u^*[1 + lnI_r^*(\gamma_{max} - \gamma)],\ (\gamma_{max} - \gamma) > S_u^*/G^* \quad (4b)$$

where p_{max} is the maximum pressure reached in the loading phase, γ_{max} is the maximum shear strain, G^* and S_u^* are the apparent shear modulus and undrained shear strength in unloading, and $I_r^* = G^*/S_u^*$. Note that most investigators use $G^* = G$ and $S_u^* = 2S_u$, with G and S_u obtained from the loading branches of the tests (see, for example, Clarke 1995).

2.2. Hyperbolic Model

a) Loading

Prevost (1976), Denby and Clough (1980), Prapaharan et al. 1989), and Ferreira and Robertson (1992) showed that pressuremeter curves could be analyzed using a hyperbolic model, implying:

$$\tau = \gamma S_u/(D + \gamma) \quad (5)$$

where D is a constant which, according to Prevost (1976), varies from 1/800 to 1/500 for most clays. Equation 5 allows finding the shear modulus at the origin $G_o = S_u/D$. In addition, the applied radial pressure p is given by

$$p = p_o + ln(1 + G_o\gamma/D) \quad (6)$$

b) Unloading

For the unloading phase, Eqs. 5 and 6 become respectively:

$$\tau^* = S^*(\gamma_{max} - \gamma)/(D^* + \gamma_{max} - \gamma) \quad (7)$$

and

$$p = p_{max} - S_u^* ln[1 + G_o^*(\gamma_{max} - \gamma)/D^*] \quad (8)$$

where S_u^*, G_o^*, and D^* refer to the unloading phase.

2.3. General Response (Palmer' approach)

The small-strain stress-shear strain and radial pressure-shear strain relationships in loading which are obtained from the solution found by Baguelin et al. (1972), Ladanyi (1972), and Palmer (1972) are the following:

$$\tau = \gamma\, dp/d\gamma \quad (9)$$

and

$$p = p_o + \int \tau\, d\gamma/\gamma \quad (10)$$

where $dp/d\gamma$ is the slope of the experimental pressure-expansion curve.

3. Analysis of Field Test Results

3.1. Stiff Clay Deposit

PMTs were carried out at depths of 4.5 $(4.4 - 4.6)$ and 6.5 $(6.0 - 7.0)\ m$. The pressuremeter used is a Texam NX probe (Felio and Briaud 1986; Marcil et al. 2015; Marcil 2020), Roctest Ltd., St. Lambert, Quebec. The radial deformation rate used was $1\%/min$, following the recommendation of Baguelin et al. (1986) to minimize excess pore pressure dissipation. With a diameter D of 70 mm and a length of 360 mm, the length-to-diameter ratio L/D of the Texam probe is 5.1. The PMTs reported in the present paper consisted of loading and unloading phases. It should be noted that the initial diameter of the pilot holes, which were drilled prior to the performance of PMTs, was equal to 73 mm. In addition, as the pilot holes were dry, the initial state of the clay for these tests was represented by $p_o = 0$ and γ_o equal to a yet-to-determine negative value caused by drilling of the boreholes.

SBPMTs were carried out by means of a Cambridge self-boring instrument, model Mark VIII, Cambridge In-Situ, Cambridge. The flexible membrane has a diameter D of 83 mm and a length L of 480 mm, giving a length-to-diameter ratio L/D of 5.8. Two pore pressure gauges fixed to the flexible membrane allowed the measurement of pore water pressures generated during the tests. The probe was expanded at a radial pressure rate of $18\ kPa/min$, resulting in an average radial strain rate of $1.09\%/min$. Unloading phases were not performed in these tests. For the SBPMTs the lift-off pressure p_o was considered to be approximately equal to the initial in situ horizontal pressure σ_{ho}. These tests were thus considered as ideal pressuremeter tests. SBPMTs were carried out at depths of 4.5 and 6.5 m.

3.2. Discussion and Comparison of Test Results

PMT load-reload curves are shown in Fig.1. Loading curves obtained in the SBPMTs are reported in Fig. 2. Table 1 presents average values of G, S_u, I_r, G_o, D and G^*, S_u^*, I_r^*, G_o^*, D_o^* determined by means of Eqs. 1, 3a, 5, and 7. For example, the average value of the rigidity index I_r for the clay at $4.5m$ equals 45 in loading and 31 in unloading in the case of the elastic-plastic model. In addition, the parameter D for the hyperbolic model equals $1/114$ or 0.00877 in loading and $1/74$ or 0.01348 in unloading for the clay at $4.5\ m$. The corresponding values of D for $z = 6.5\ m$ are equal to $1/114$ in loading and $1/62$ in unloading.

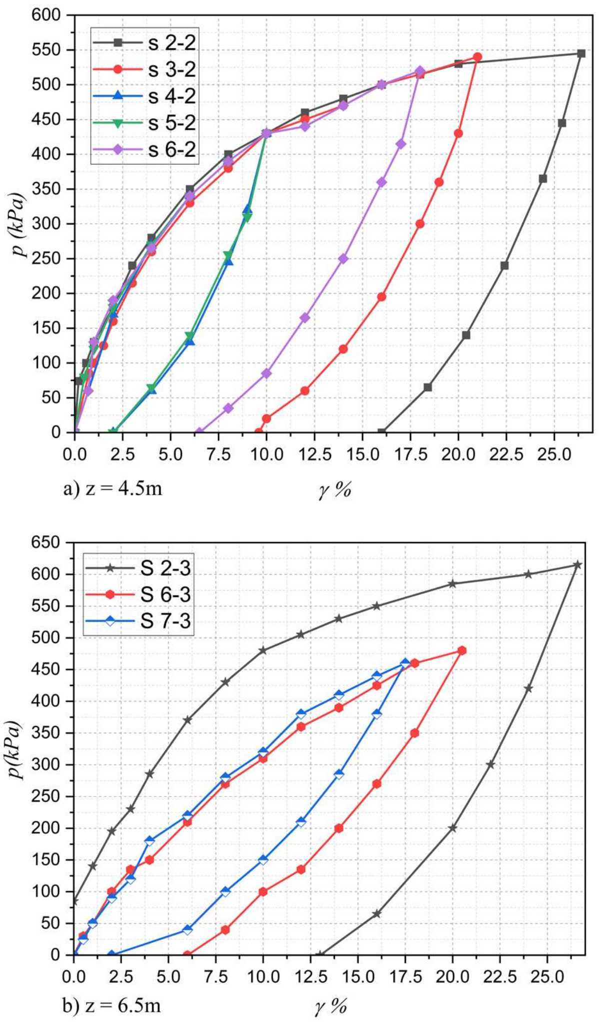

Figure 1. PMT load-unload expansion-contraction pressure-shear strain curves.

The various entries in Table 1 also show that while the ratio S_u^*/S_u varies between 1.39 and 1.52, that of G^*/G averages 0.92 for the ideally elastic-perfectly plastic model and varies between 0.9 and 0.99 for the hyperbolic model. It should be noted that most investigators assume that $S_u^*/S_u = 2$ and that $G^*/G = 1$ (See, for example, Houlsby and Withers (1988), and Ferreira and Robertson (1992)).

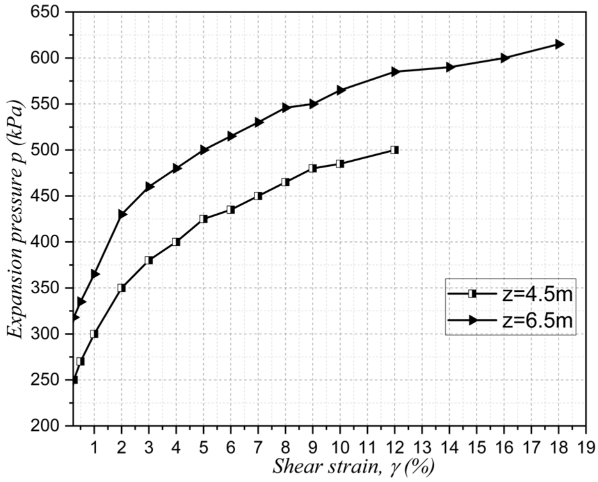

Figure 2. SBPMT expansion pressure-shear strain curves.

Table 2, which presents values of the in- situ coefficient of lateral earth pressures at rest, K_o, shows that K_o varies between 3.6 and 3.9, based upon SBPMT lift-off pressures. Table 2 also gives initial, total and effective vertical stresses, σ_{vo} and σ'_{vo}. Table 3 presents SBPMT-deduced clay parameters. For the clay at 4.5 m, the rigidity index I_r equals 94 in the case of the elastic-plastic model. As for the hyperbolic model, the parameter $D = 0.00408$ or 1/245 for the test at 4.5 m. Concerning Palmer's approach, it was found that differentiation of the experimental radial pressure-shear strain curve yielded a peak undrained shear strength of 76 kPa at a shear strain of 0.0195.

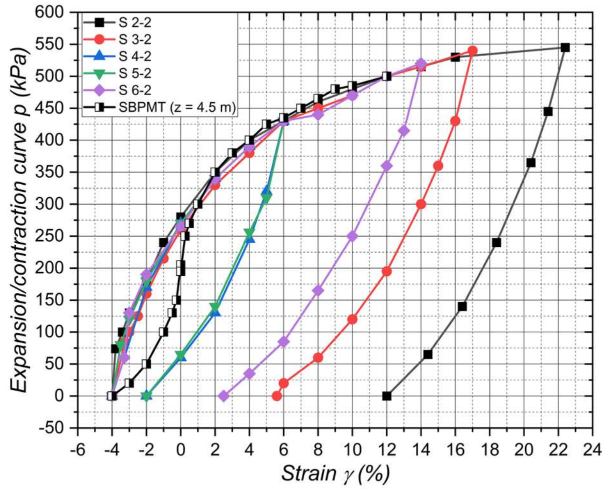

Figure 3. Adjusted PMT curves ($z = 4.5\ m$).

A rapid comparison between the parameter reported in Tables 1 and 3 indicates that while S_u and S_u^* values deduced from the PMTs are practically equal to twice the corresponding S_u values obtained from the SBPMTs, the values of G^* are in the same range of magnitude as the values of G found from the SBPMT data, for both the elastic-plastic and the hyperbolic models.

In view of the preceding results, the PMT-deduced curves were re-analyzed by taking into account the fact that there must have existed an initial negative shear strain γ_o at the beginning of the performance of the expansion phases of these tests, following the drilling of the pilot holes. On the basis of the investigations carried out by Prevost (1979), Prapaharan and Chameau (1998), Silvestri (2004), and Silvestri and Abou-Samra (2008), loading curves derived from the SBPMTs were considered to apply also in unloading. As a consequence, the initial negative shear strain caused by drilling of the pilot holes was determined from the experimental curves. For example, in the case of the tests carried out at a depth $z = 4.5\ m$, the negative shear strain $\gamma_o = 0.04\ or\ 4.0\%$ for $p_o = \sigma_{ho} = 195\ kPa$. Thus, the PMT-deduced radial pressure-shear strain curves are assumed to begin at $p_o = 0$ and $\gamma_o = -0.04\ or - 4.0\%$, as shown in Fig.3. As for the PMTs carried out at 6.5 m, the initial negative shear strain $\gamma_o = -0.09\ or - 9.0\%$.

The procedure just described consists in considering the SBMPT-deduced pressuremeter curves as backbone or skeleton curves in a Masing model (Prevost 1979). Examination of the PMT-translated curves in Fig.3 indicates that the adoption of the Masing model is quite reasonable. A similar result is found for the PMT S2-3 performed at 6.5 m, as shown in Fig. 4. However, for the PMTs S6-3 and S7-3 for which drilling remoulded the walls of the boreholes prior to the performance of the expansion/contraction tests, the agreement is rather poor. An indication that there was possibly an initial disturbance in the latter tests is given by the decreased value of the rigidity index of 20 compared to 44 for the test S2-3 in loading.

Table 1. PMT-deduced clay parameters

	Loading						Unloading					
	Elastic-Plastic			Hyperbolic			Elastic-Plastic			Hyperbolic		
Depth $z\ (m)$	G (kPa)	S_u (kPa)	I_r	G_o (kPa)	S_u (kPa)	D	G^* (kPa)	S_u^* (kPa)	I_r^*	G_o^*	S_u^*	D^*
$\mathbf{4.5m}$	7400	166	45	18935	166	1/114	7125	230	31	17065	230	1/74
$\mathbf{6.5m}$	8010	183	44	18550	183	1/114	7395	278	27	17325	278	1/62

Table 2. SBPMT-deduced values of K_o

Depth $z\ (m)$	$\boldsymbol{\sigma_{vo}\ (kPa)}$	$\boldsymbol{u_o\ (kPa)}$	$\boldsymbol{\sigma'_{vo}\ (kPa)}$	$\boldsymbol{\sigma_{ho}\ (kPa)}$	$\boldsymbol{\sigma'_{ho}\ (kPa)}$	$\boldsymbol{K_o}$
$\mathbf{4.5m}$	72	30	166	195	165	3.9
$\mathbf{6.5m}$	104	44	183	276	232	3.9

Table 3. SBPMTs deduced clay parameters

	Elastic-Plastic			Hyperbolic			Palmer	
Depth $z\ (m)$	$\boldsymbol{G\ (kPa)}$	$\boldsymbol{S_u\ (kPa)}$	$\boldsymbol{I_r}$	$\boldsymbol{G_o\ (kPa)}$	$\boldsymbol{S_u\ (kPa)}$	$\boldsymbol{D}$	$\boldsymbol{G_o\ (kPa)}$	$\boldsymbol{S_u\ (kPa)}$
$\mathbf{4.5m}$	7400	166	45	18935	166	1/114	15635	76
$\mathbf{6.5m}$	8010	183	44	18550	183	1/114	11735	86

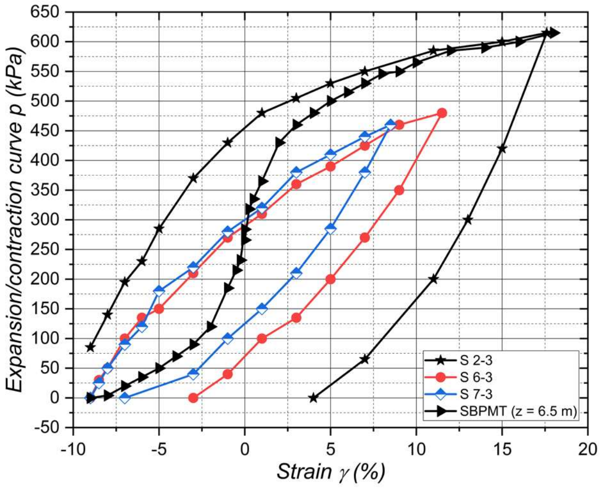

Figure 4. Adjusted PMT curves ($z = 6.5\ m$).

As a final discussion about the field tests, Table 4 summarizes the values of the undrained shear strength obtained by means of vane shear tests (VSTs) and compares them with corresponding values deduced from the loading phases of the SBPMTs. Examination of the various entries in this table shows that the SBPMT-deduced S_u values are roughly equal to 1.1 those found from the VSTs. Thus, for the stiff clay at study, values of undrained shear strength deduced from SBPMTs are not overly exaggerated compared to VST-determined values.

Table 4. Comparison between SBPMT and VST results

Depth z (m)	$S_u(kPa)$		S_{uSBPT}/S_{uVST}
	SBPMT	**VST**	**1.24**
4.5	89	72	1.11
6.5	89	80	0.84
7.7	87	103	1.06

4. Conclusions

On the basis of the results reported in this paper, the following conclusions are drawn:

1) SBPMT-deduced curves are found to correspond to backbone curves of the Masing model. PMT-deduced load-unload branches are considered as reload-unload branches of the backbone SBPMT curves.
2) The self-boring tests (SBPMTs) give strength values that compare favourably with those measured by field vane tests.
3) Prebored pressuremeter tests (PMTs) overestimate considerably the values of the undrained shear strength S_u of the stiff clay compared with those found from the vane shear tests.

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